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UNIVERSITY OF TORONTO

FINAL TECHNICAL REPORT

ON

AEROPHYSICAL ASPECTS OF GAS AND PLASMA FLOWS

AF-AFOSR-77-3303

1 APRIL, 1977 - 31 JANUARY, 1982

by

I. I. Glass

31 MARCH, 1982

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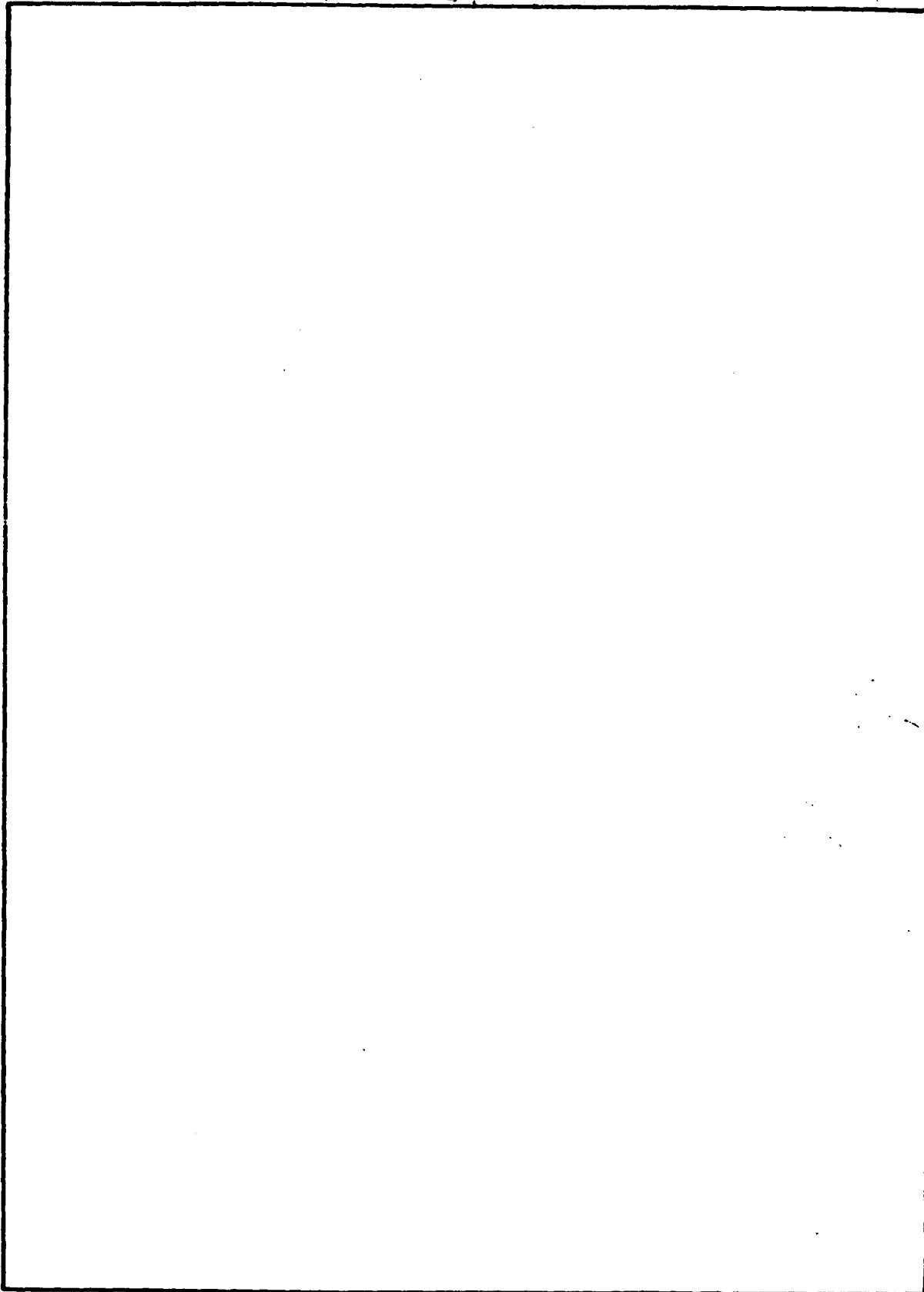
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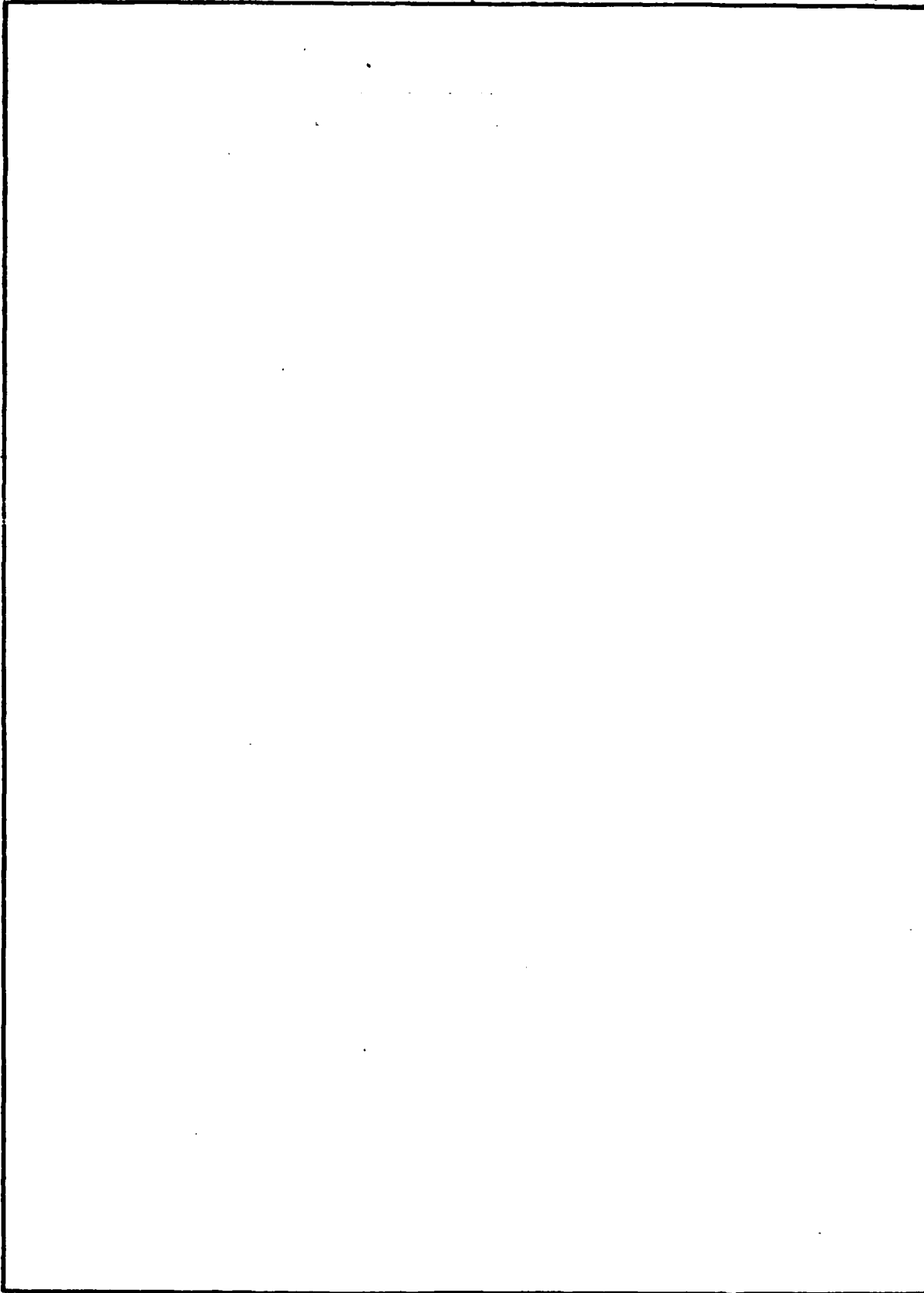
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Table of Contents

AFOSR-77-3303 FINAL TECHNICAL REPORT

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1) Abstract

We have provided the only significant experimental and analytical data on pseudo-stationary oblique-shock-wave reflections in monatomic (Ar), diatomic (O_2, N_2, air), triatomic (CO_2) and polytomic (SF_6) gases in the form of isopycnics and shock Mach number - wedge angle (M_s, θ_w) - plots of value to the military (AFWL, DNA, ARO, BRL, NSWL, DRES, etc.), industry (R & D Associates, Physics International, NASA, etc.) and universities. Our laboratory results have been invaluable to field experiments and to computational fluid dynamicists. The latter have had to develop new, improved codes to match our accurate experimental data.

Our results on the production of neutrons and γ-rays by explosive-driven implosions in D_2 have now been published. They have attracted an international interest. The method provides a simple means of studying fusion plasmas at extreme temperatures and pressures as well as solid-phase transitions from carbon to diamond and other new materials.

The reports on the dynamics of dusty-gas flows produced by shock waves are "best-sellers" and are out of print. We hope to test our analyses in our new 10cm x 20cm dusty gas shock tube built for this purpose during the year with funds from the Canadian Defence Research Establishment Suffield (DRES). The analytical and experimental data has important applications to combustion, dust explosions, damage from blast waves and cosmic gasdynamics.

Our extensions of the random choice method (RCM) have aided us (and others) greatly in analyzing explosion-implosion dynamics, detonations, dusty-gas flows, and viscous heat-conducting vibrationally-excited shock-wave transitions in air for weak spherical N-waves.

The virtue of this method is that it does not suffer from artificial viscosity (implicit or explicit) smearing of shock waves and contact surfaces. If some method could be found to apply RCM to pseudo- and non-stationary flows, it would revolutionize computational shock fluid dynamics.

Our analytical work on swirling turbulent combustion flows has progressed very well. Experimental data are now being accumulated using laser Doppler anemometry (LDA). This work is not only of interest to researchers in various establishments (including AFOSR) but to industry as well. In this regard, we have received some financial support from Canadian Pratt and Whitney to set up the LDA equipment.

2) Research Objectives

The research objectives are to make significant advances in the field of "Aerophysical Aspects of Gas and Plasma Flows", useful to the varying supporting agencies and to research and development in industry. Our objectives have been met to a large extent. This statement can be verified from our numerous publications in distinguished journals and by our peers in the field internationally.

3) Detailed Summary and Perspectives

Although the phenomenon of oblique-shock-wave reflections has been known for a long time, it is only within the period of this Grant that order and understanding has been brought to this subject. Once and for all, we have shown that the domains and boundaries of regular (RR), single-Mach (SMR), complex-Mach (CMR) and double-Mach reflections (DMR) can be plotted as a function of the initial conditions, namely, shock wave Mach number M_s and wedge angle θ_w -plane, for a perfect gas. If real-gas effects take place then the initial temperature T_0 and pressure p_0 must

be added. The results for argon (monatomic gas) are shown in Fig. 1.
It is seen that the analysis is good and agrees with experiment for a
perfect gas in the range tested for $M_s<10$. The results for air, N_2 and
O_2 (diatomic gases) appear in Fig. 2. It can be seen that the agreement
with a perfect gas in this case is quite good except for the SMR⇆CMR
transition line. The experimental data consists of our own work and from
others. Figure 3 shows the results for CO_2 (a triatomic linear molecule).
Again the data agree well with analysis in the range $1<M_s<10$.

These two-dimensional data along with interferometric plots of
lines of constant density (isopycnics have formed the basis for testing
the validity of several computational methods of predicting the flow
quantities. So far, the computational schemes are quite good for
predicting shock shapes and wall-density distributions but poor for
giving results on isopycnic shapes and distributions. These disagreements
are being investigated by many government, university and industrial
establishments in a number of countries. Undoubtedly better computational
procedures will evolve in the near future.

The foregoing laboratory results have been successfully applied
by AFWL, DNA and BRL among others to predict shock-wave configurations
and pressure loadings in field tests on vehicles and missile sites.

The transition lines themselves must be fine-tuned in order to
improve the agreement between analysis and laboratory experiments. A
great deal has already been done in this respect and this will be the
subject of future reports under the new Grant AF-AFOSR-82-0096.

The production of fusion plasmas in deuterium cannot be described
more simply than in the brief paper in Physics of Fluids by Glass and
Sagie, "Application of Explosive-Driven Implosions to Fusion", (Ref. 1).
A copy is enclosed. This unique method of producing neutrons, γ-rays

and solid-phase transitions (graphite to diamond of 10-20μm dia)
offers simple, new possibilities for many avenues of physical research
of interest to industry, universities and the military. As a matter
of fact, 3M of Canada, who are interested in industrial diamonds, have
taken up our research and development program on the use of explosive-
driven implosions to generate diamonds from graphite. Several R & D
personnel from 3M are stationed at our Institute pursuing this work.
It is an excellent example of technology transfer from a university
to industry.

Although the dynamics of dusty-gas flows is of much importance
to science, industry and the military, very limited research and develop-
ment was conducted in the past in this field. In a more practical
vein, very little is known about nonstationary drag and heat transfer
experienced by individual particles accelerated by shock or blast waves.
Neither is it known precisely what impact pressure such flows impose
on structures, nor what damage may result to vehicles, hardened missile
sites or buildings affected by high-speed high-pressure dusty-gas flows.
In order to understand such problems, the two avenues of analysis and
experiment have been undertaken. Our analytical work on the flow in
a dusty-gas shock tube (Figs. 4 to 6) and the passage of a shock wave
through a dusty-gas layer (Figs. 7 and 8) (in great demand internationally),
will form the basis for our experimental work. For the latter, we have
built and will instrument a 3-3/4 x 8 in. dusty-gas shock tube 60 ft.
long, in order to check our analyses by using glass spheres as homogeneous
dust in the 10-50μm range. Optical methods, laser Doppler anemometry,
pressure gauges, impact gauges, heat-transfer gauges and other devices
will be used for this purpose. We estimate the dusty-gas shock tube
will cost $500,000.00 and it is being supported by Canadian funds. Here

is an excellent example of AFOSR benefits coming from an almost
entirely Canadian funded project.

The random-choice method (RCM) of analyzing nonstationary planar,
cylindrical and spherical flows with shock waves has proven to be
one of the most powerful and accurate computational methods available
today. Its power and accuracy lies in the fact that it makes no use
of finite difference methods which suffer from an inherent explicit or
implicit artificial viscosity that smears shock fronts and contact
surfaces in a flow. Instead it solves the Riemann problem at each time
step in the numerical analysis in a random fashion. The results provide
sharp fronted shocks and contact surfaces. This method has been applied
successfully at our Institute to numerous problems such as explosion,
implosion and detonation-wave dynamics, nonlinear planar-wave interactions
and dusty-gas dynamics. However, we have also succeeded in using the
method for spherical N-wave shock-front transitions with viscosity,
heat conductivity and vibrational excitation. The N-waves were
generated by exploding wires. The explosion process was modelled by
considering the N-waves produced by a small pressurized   sphere
which is suddenly ruptured. The sphere diameters and the initial
conditions determine the properties of the N-waves that simulate those
actually obtained from exploding wires. Some of the results appear in
Figs. 9 and 10. The comparison between analysis and experiment is
good. This research will help us understand the properties of N-waves
generated in the atmosphere by SST's and will explain the order-of-
magnitude discrepancy between measured and predicted risetimes of sonic
boom N-waves. The risetime controls the human-startle effect. The
shorter the risetime (microseconds), the more annoying is the boom.

So far the RCM has been successful in treating nonstationary one-

dimensional flows. What is required for the treatment of pseudo-stationary two-dimensional oblique-shock-wave reflections or nonstationary spherical shock-wave reflections is a RCM algorithm to handle such complex flows. So far, despite the endeavours of many able computational fluid dynamicists, the search has proved to be very elusive.

The analytical-numerical program with coupled gasdynamic and chemical-dynamic equations of motion to deal with turbulent, swirling, combusting flows has been completed. Now emphasis has been placed on laser Doppler anemometer (LDA) experimentation shakedowns in order to measure the turbulence components and Reynolds stresses at a given station of a combustor. The results can then be used as data input in the analysis for predicting these quantities at any other station downstream. Their new measurements can be made at the predicted stations in order to check the various models of turbulence and the coupled equations of motion.

As a fall out of the LDA work, it has been confirmed that particle size and their velocity can readily be measured to 1%. This will make it possible to measure fuel-spray size and velocity distributions in combustors which is of much importance to the jet-engine industry in the USA and Canada.

Finally, our research and development work in the foregoing areas is continuing in a vigorous manner. Many reports are in preparation in the five major areas considered. Several papers have been sent to distinguished journals. One has already been accepted for publication in the Proceedings of the Royal Society of London and others will follow. Details will be given under Grant AF-AFOSR-82-0096 in the near future.

Dr. I. I. Glass
Principal Investigator

4) Publications 1981-1977

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29. "Ionizing Argon Boundary Layers. Part 1. Quasi-Steady Flat-Plate Laminar Boundary-Layer Flows", by W. S. Liu, B. T. Whitten and I. I. Glass, J. Fluid Mech., Vol. 87, Part 4, pp. 609-640, 1978.

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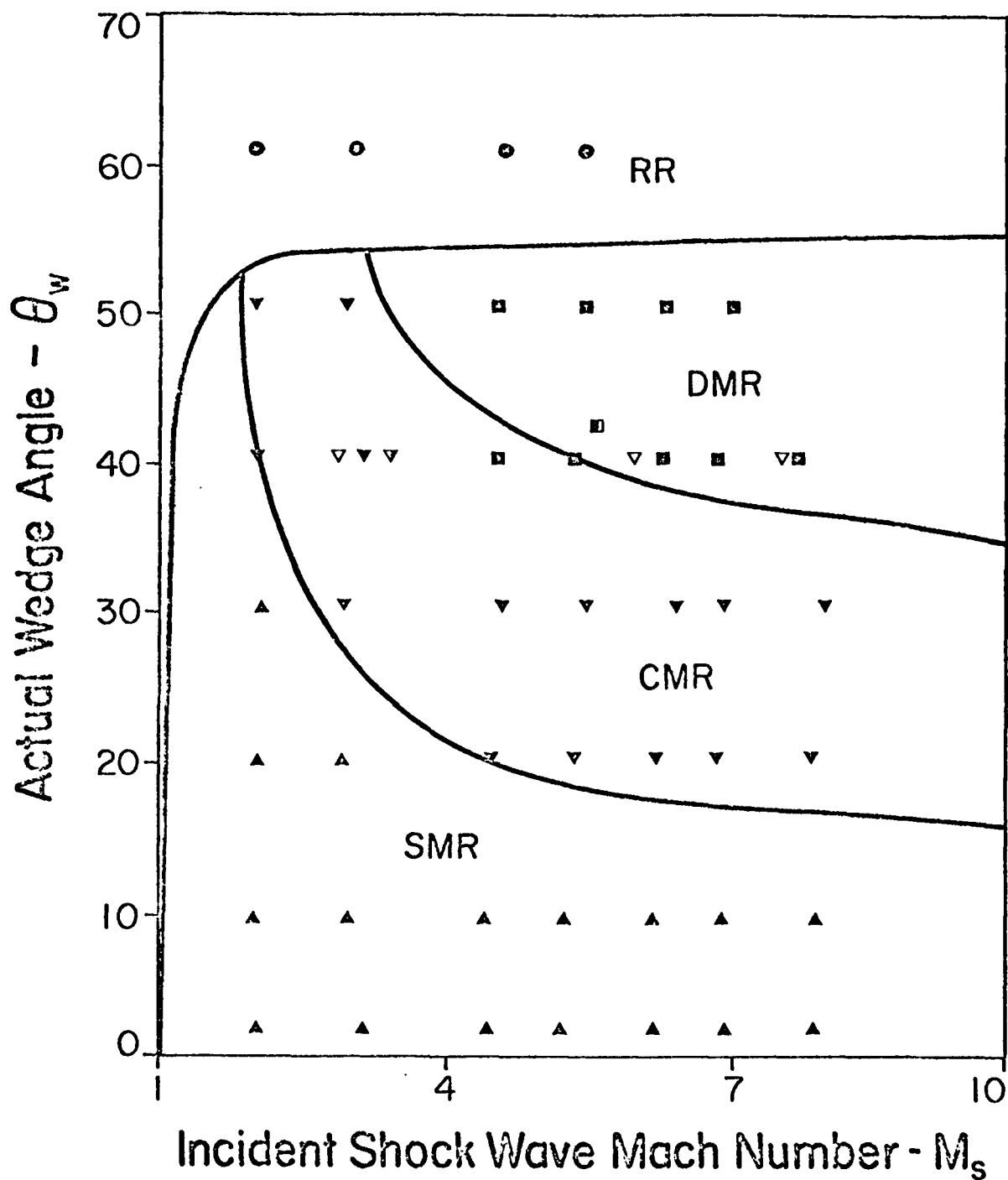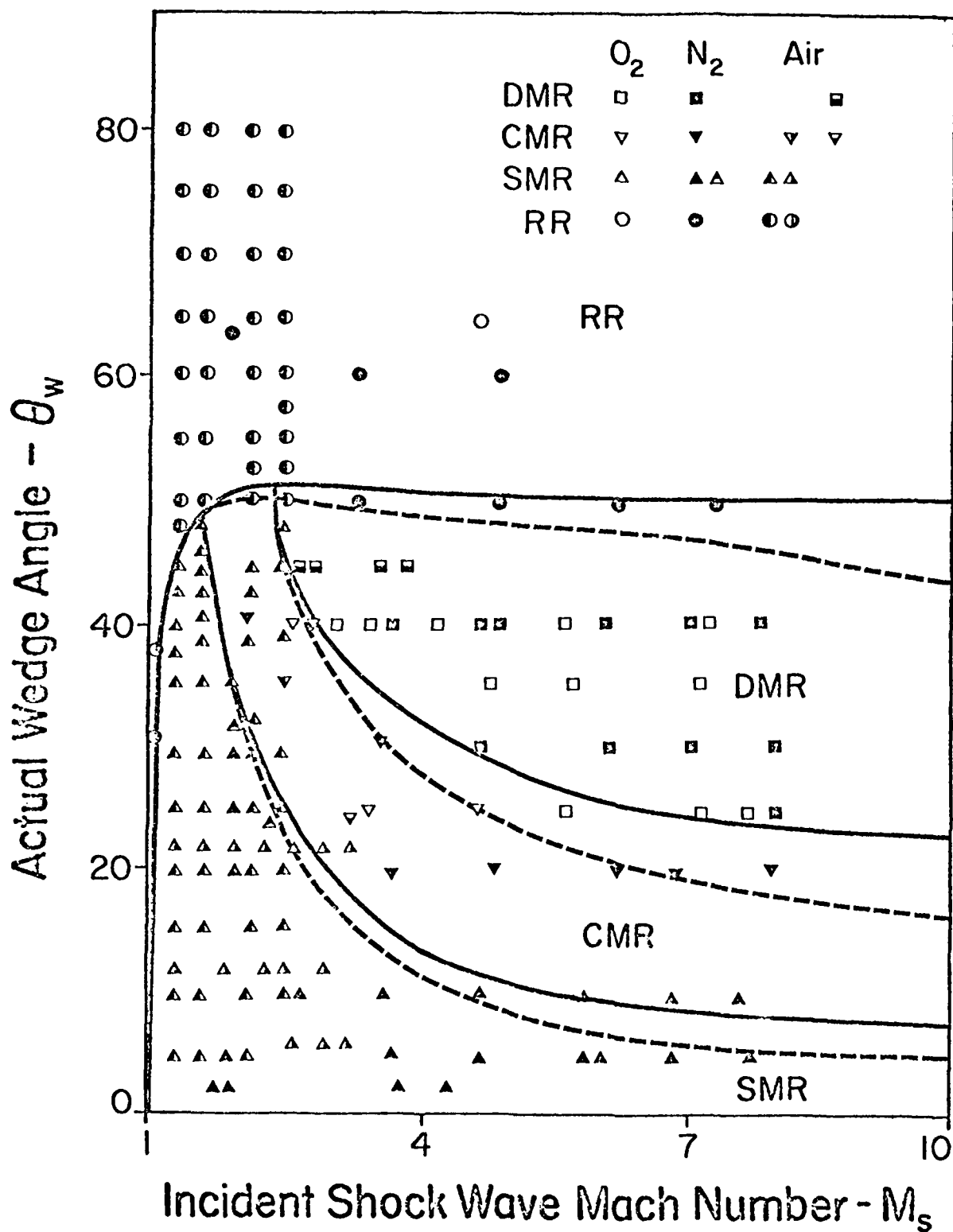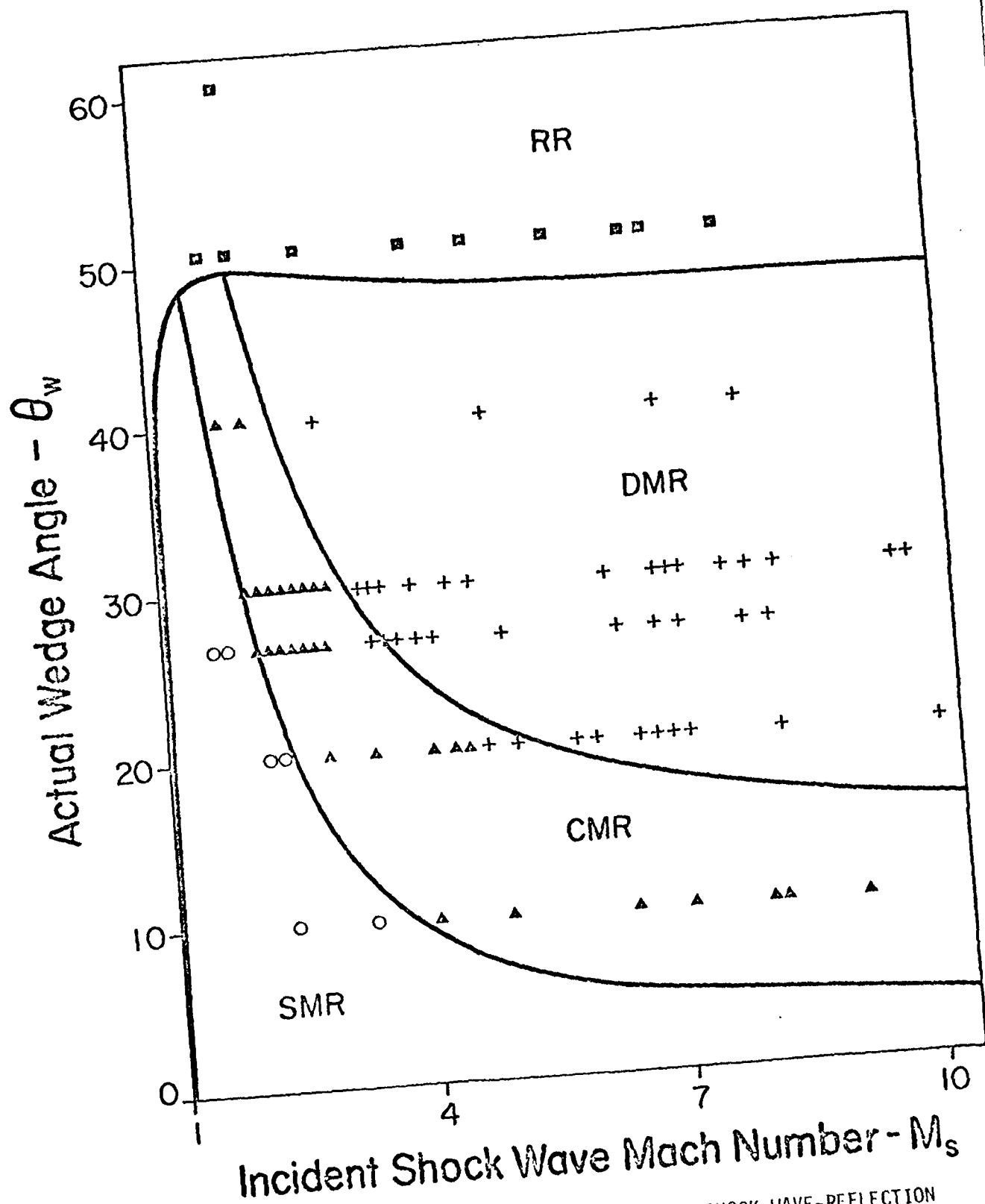
FIG. 1 EXPERIMENTAL VERIFICATION OF OBLIQUE SHOCK-WAVE-REFLECTION
REGIONS AND BOUNDARIES IN THE (M_S, θ_W)-PLANE. PERFECT MONATOMIC
GAS $\gamma = 1.667$, LAW (1970), CMR IN HELIUM ($\blacktriangledown$); LAW AND GLASS
(1971) CMR IN ARGON ($\triangledown$), BAZHENOVA ET AL. (1976) DMR IN ARGON ($\square$).
PRESENT RESULTS IN ARGON: $\blacksquare$, DMR; $\blacktriangledown$, CMR; $\blacktriangle$, SMR; $\bullet$, RR.

FIG. 2 EXPERIMENTAL VERIFICATION OF OBLIQUE SHOCK-WAVE-REFLECTION
REGIONS AND BOUNDARIES IN THE (M_s, θ_w)-PLANE. PERFECT DIATOMIC
GAS $\gamma = 1.400$. -----REAL GAS. $\triangle$, $\odot$, AIR (DATA FROM SMITH
1945); $\blacktriangledown$, $\triangle$, O, AIR (WHITE 1951); $\square$, $\triangledown$, $\triangle$, O, OXYGEN (LAW
AND GLASS 1971); $\blacksquare$, $\blacktriangledown$, AIR (BAZHENOVA ET AL. 1976); $\blacktriangle$,
NITROGEN (BAZHENOVA ET AL. 1976); $\blacksquare$, $\blacktriangledown$, $\blacktriangle$, $\bullet$, NITROGEN (BEN-DOR
AND GLASS 1978).

FIG. 3 EXPERIMENTAL VERIFICATION OF OBLIQUE SHOCK-WAVE-REFLECTION REGIONS AND BOUNDARIES IN THE (M_S, θ_w)-PLANE FOR A TRIATOMIC GAS CO_2 $\gamma = 1.290$. ▣ = RR, O = SMR, ▲ = CMR, + = DMR.
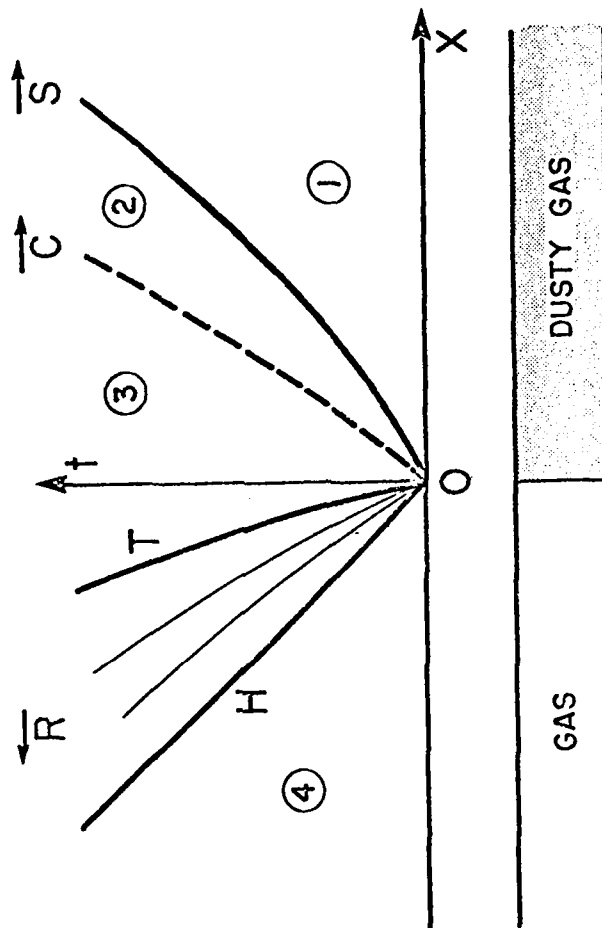
Fig.4 Schematic diagram of flow in a dusty-gas shock tube after diaphragm rupture.

$\overleftarrow{R}$ = rarefaction wave, $\overrightarrow{C}$ = contact front, $\overrightarrow{S}$ = shock front, H = head, T = tail.

Fig.5 Flow quantities at $\tau = 4$ ($\alpha = 1$, $P_{41} = 10$, $d = 10$ μm).
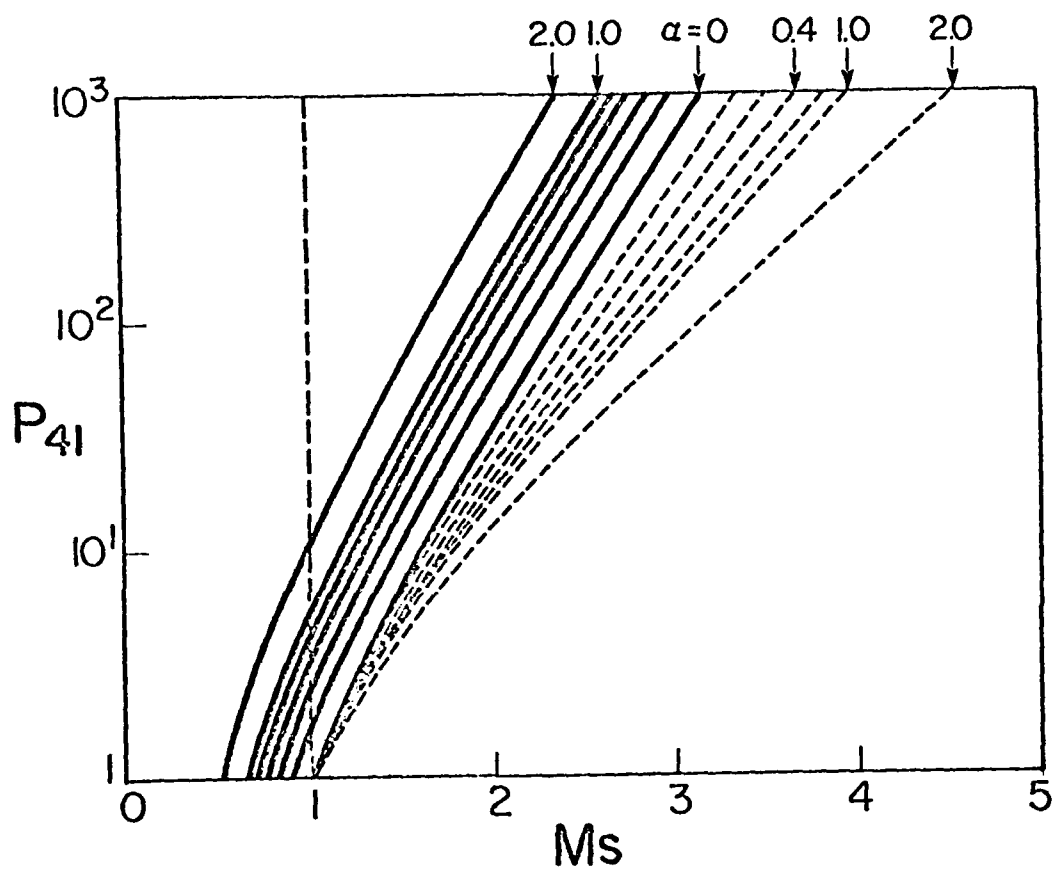———— gas, —·— particles, ------ frozen flow.

Fig.6 Variation of shock wave Mach number M_s with diaphragm pressure ratio P_{41}. ———— M_s based on frozen speed of sound a_{1f}, — — — M_s based on equilibrium speed of sound a_{1e}.
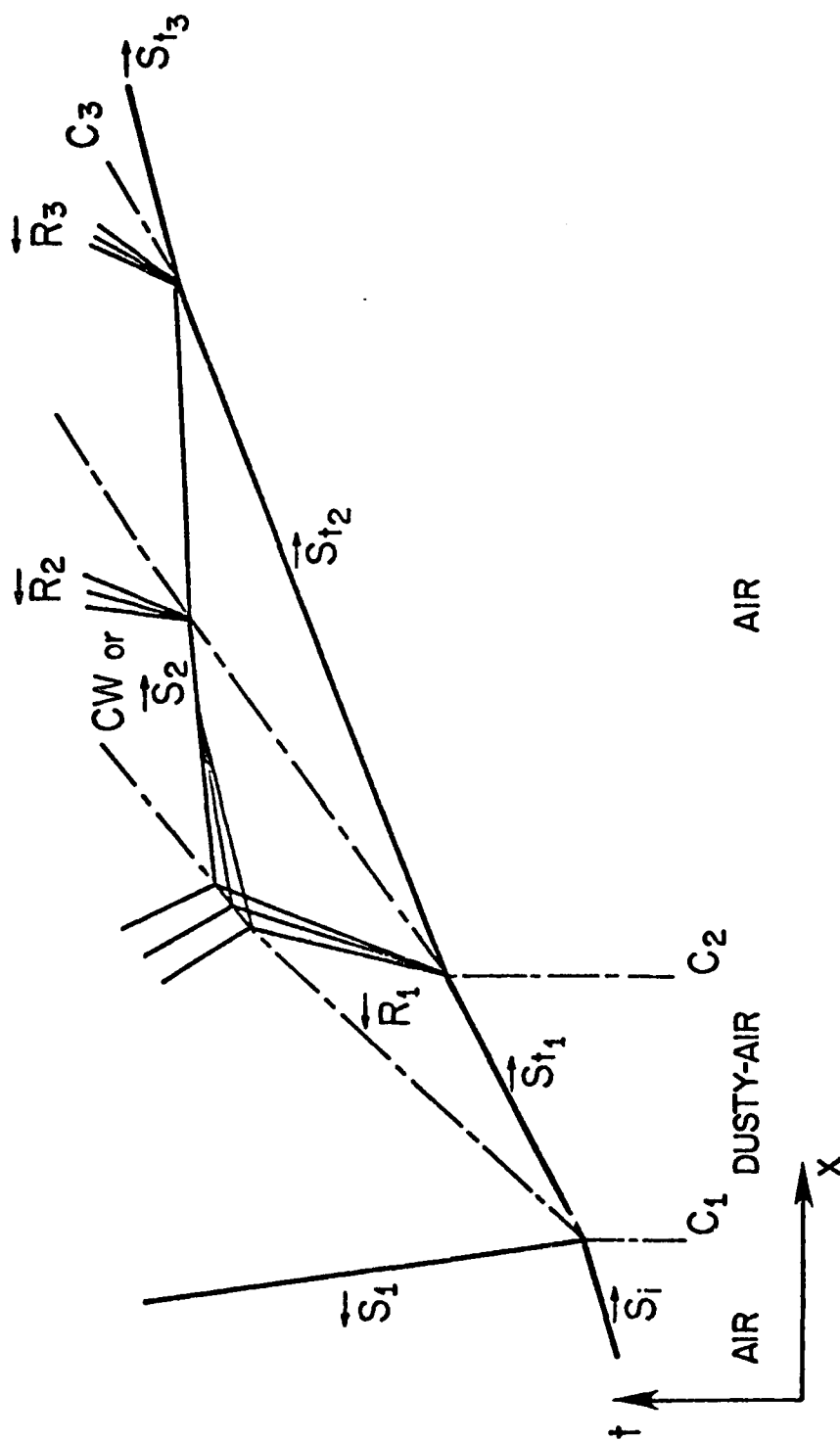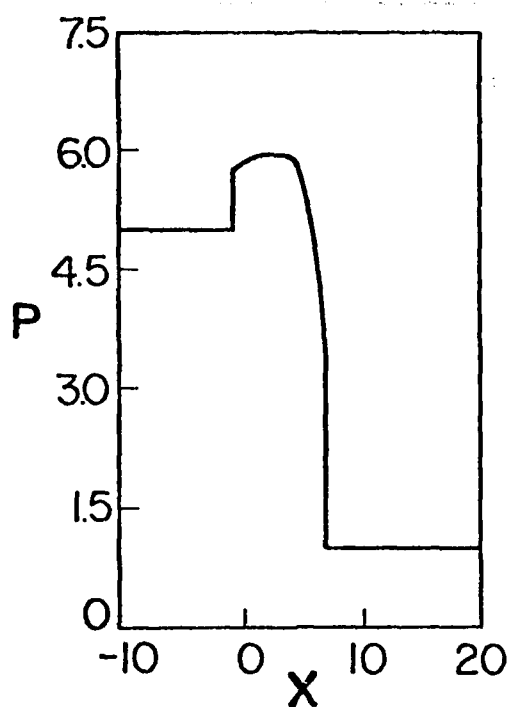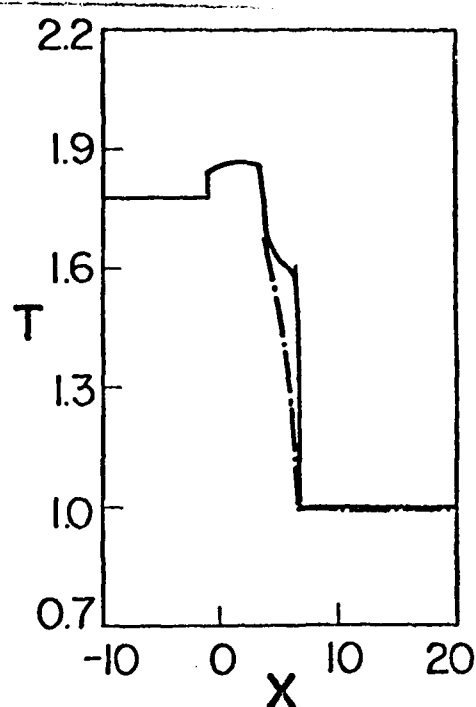
FIG. 7   SCHEMATIC x-t DIAGRAM OF THE PASSAGE OF A SHOCK WAVE THROUGH A
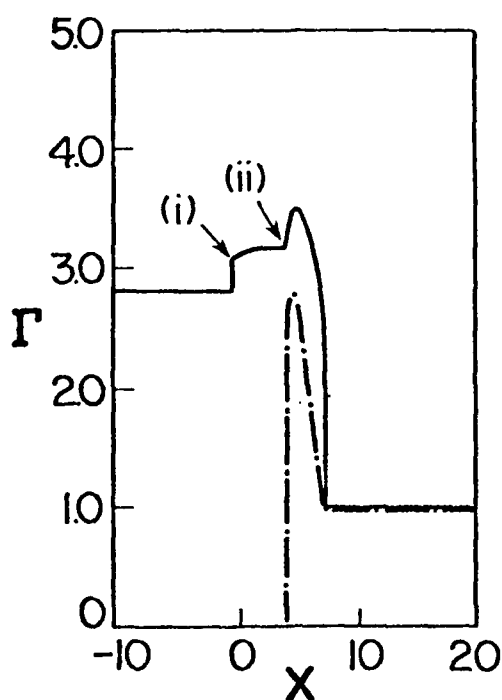   DUSTY-AIR LAYER.

S_i: INCIDENT SHOCK WAVE, S_t: TRANSMITTED SHOCK WAVE, C: CONTACT
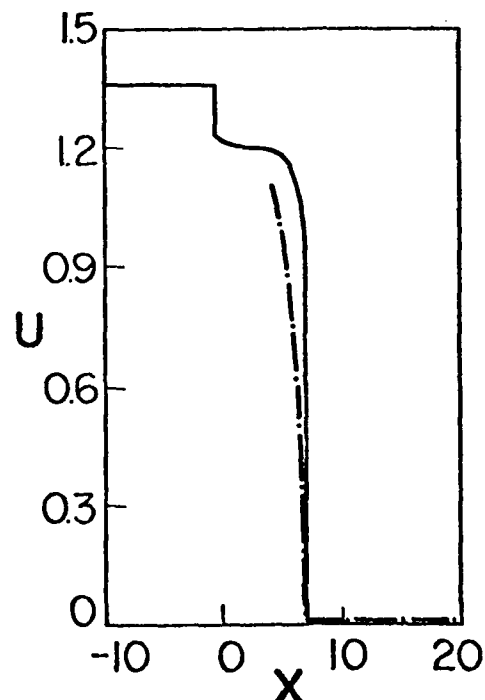FRONT, S: INDUCED SHOCK WAVE, R: INDUCED RAREFACTION WAVE,
CW: COMPRESSION WAVE.

FIGURE 8. Flow quantities at t = 3.12×10^{-4} s ($p_4/p_5 = 5$). (a) Pressure, (b) Mass concentration, (c) Temperature, (d) Velocity. ———— gas, – – – – particles. (i) Beginning of formation of a reflected shock wave, (ii) Beginning of formation of a contact region.

Table.1 Initial conditions for computation.

| No.	P_4	T_1 (K)	R_h (%)	R_0 (cm)	h	ΔX (cm)	vibrational relaxation	
A	2.44	273	—	1.15	—	0.0383	—	perfect, inviscid
B	2.44	273	—	1.15	—	0.0383	—	perfect, viscous
C	2.44	273	67	1.15	0.404	0.0383	O_2	real, inviscid
D	2.44	273	67	1.15	0.404	0.0383	O_2	real, viscous
E	1.8	289	50	1.15	0.888	0.0383	O_2	real, viscous
F	1.8	273	67	1.15	0.404	0.0383	O_2	real, viscous
G	1.8	289	50	11.5	0.888	0.383	O_2	real, viscous
H	1.8	289	50	57.5	0.888	1.917	O_2	real, viscous
I	1.8	289	50	57.5	0.888	1.917	$O_2 + N_2$	real, viscous
J	1.8	289	—	1.15	—	0.0383	—	perfect, inviscid
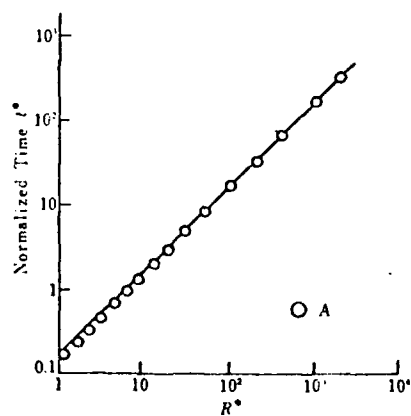
Fig. 9 Path of shock front.

$$t^* = \frac{a_1 t}{5\sqrt{\gamma} R_0}, \quad R^* = R/R_0$$

a_1 : speed of sound
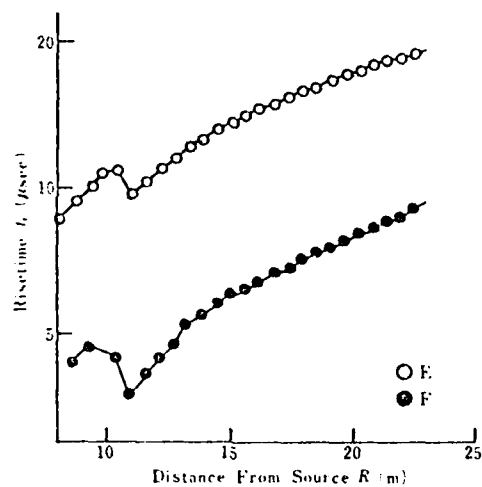
R_0 : radius of pressurized sphere
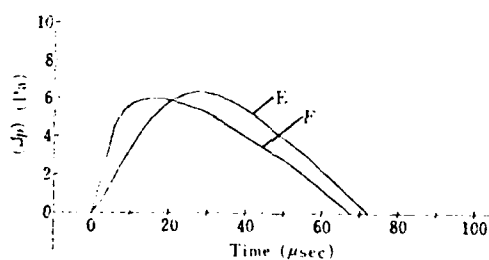
Fig. 10a   Risetime as a function of distance(II).

Fig.10b   Comparison of pressure profiles(II).

E : $R = 19\,\text{m}$, $(\Delta p)_{max} = 6.33\,\text{Pa}$, $t_r = 16.78\,\mu\text{sec}$, $t_d = 69.37\,\mu\text{sec}$

F : $R = 19\,\text{m}$, $(\Delta p)_{max} = 6.0\,\text{Pa}$, $t_r = 7.7\,\mu\text{sec}$, $t_d = 66.3\,\mu\text{sec}$

Application of explosive-driven implosions to fusion

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Our explosive-driven implosion facility was used to produce hemispherical implosions in a stoichiometric mixture of deuterium-oxygen. A high-resolution scintillator detection system measured neutrons and γ rays resulting most likely from the fusion of deuterium.

I. INTRODUCTION

The Institute for Aerospace Studies hemispherical implosion chamber is a unique device for producing explosive-driven implosions which are stable and well-focused at the geometric center in a safe and reusable facility.[1] It has been used as a driver for launching hypervelocity projectiles,[2] to generate intense planar shock waves,[3] and to produce diamonds from graphite.[4] In the present study is was utilized to bring about fusion in a deuterium-oxygen plasma.

II. EXPERIMENTAL EQUIPMENT

The implosion chamber (Fig. 1) consists essentially of two massive mating steel plates. The rear plate contains a 20-cm diam hemispherical cavity. Into it is fitted an explosive package consisting of a copper liner to which is bonded a shell of superfine PETN secondary explosive (of about 3 mm in thickness weighing 97 g and releasing about 0.6 MJ of energy for the case reported). The front plate contains an exploding nickel wire (0.13-mm diam×1-mm long) and the gas inlet and outlet. Both plates are fastened together by 32 bolts. The hemispherical cavity is filled with a stoichiometric mixture of deuterium-oxygen (in this case about 55 atm releasing about 0.4 MJ of energy). The gas is detonated at the geometric center by the exploding wire. The gaseous detonation wave instantly and simultaneously explodes the PETN on impact, thereby generating a well-focused implosion wave. This wave reflects at the geometric center, leaving a small pocket of plasma at extreme pressure (megabars) and temperature (millions of degrees) in which a deuterium fusion reaction occurs. To our knowledge this is the most direct method of initiating fusion using only chemical energy. We have tried other indirect methods to obtain fusion, where a small capsule containing deuterium was placed at the focal point of the implosion. One of these was successful and provided almost identical results, thereby lending support to the simple direct technique. Details can be found in Ref. 5.

The detection system for sensing neutrons and γ rays (produced by the neutrons and their interactions with the steel implosion chamber) consists of two scintillator-photomultiplier assemblies (Fig. 1). The first detector is located at the outer surface of the front plate, 30 cm from the implosion focus while the second is 80 cm from the focus. The first oscilloscope displays the entire ignition-detonation-implosion process lasting about 50 μsec and the subsequent events. The second oscilloscope is designed to display the full undisturbed shape of the first signal coming from the second detector and therefore sweeps at a rate of 50 ns/division. From its shape it would have been possible to obtain the neutron-velocity distribution and its flux. However, the second oscilloscope can only trigger if a large enough signal (~0.5 V) is produced by the first detector. This requires about two neutrons to cross the scintillator within 10 nsec. The threshold level is essential to prevent false triggering arising from the photomultiplier dark current, cosmic rays and ignition noise.

III. EXPERIMENTAL RESULTS

Records of voltage versus time from the first detector for two runs without (a) and with fusion (b) are shown in Fig. 2. Initially, there are large oscillations arising from the capacitor discharge to the exploding wire, which are damped out in about 35 μsec. In the case of no fusion when a stoichiometric mixture of H_2-O_2 is detonated, no other signals appear. However, with a stoichiometric mixture of D_2-O_2 when fusion occurs at about 50 μsec, about 20 negative signals appear in a random time and amplitude distribution over a period of about 50 μsec. The maximum amplitude of about 0.2 V corresponds to a single impact by a neutron or a γ
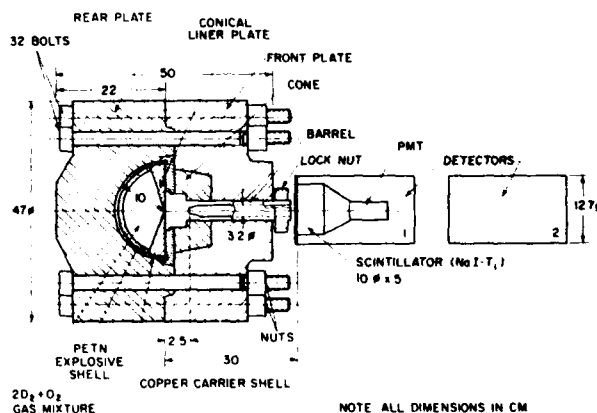

FIG. 1. Schematic of implosion-chamber facility and scintillator detectors.

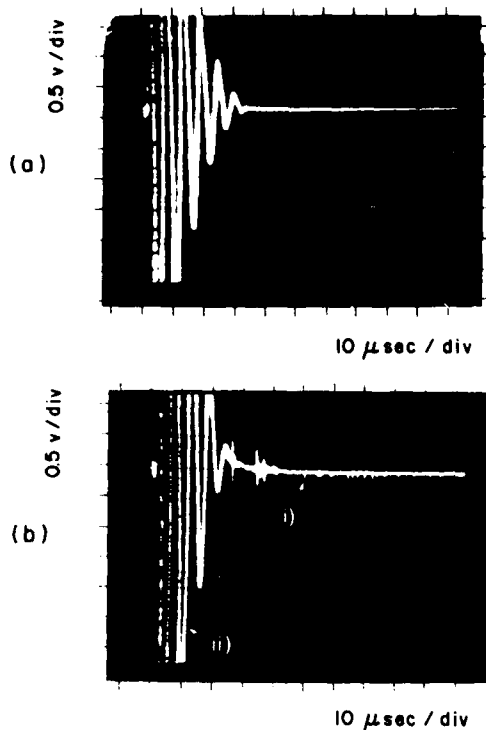[a] On sabbatical leave from the Nuclear Research Centre, Beersheva, Israel.

FIG. 2. Oscilloscope record from detector No. 1. (a) Without fusion, $2H_2 + O_2$ mixture at 27.2 atm and 127 g PETN explosive. (b) With fusion, $2D_2 + O_2$ mixture at 54.4 atm and 97 g PETN explosive; (i) arrival of implosion and beginning of events, (ii) ignition noise.

photon in the MeV range, obtained from a calibration of the scintillators at the University of Rochester. In this case the second oscilloscope did not trigger as none of the events generated a large enough signal. We estimate that the total yield was a few thousand neutrons.

The distribution of events can be explained by the scattering of neutrons as they encountered the steel chamber walls. Iron has a total cross section of about 3.5 b at 2.45 MeV.[6] Other components of the steel alloy like Mn and Co also contribute to the neutron scattering. Inelastic scattering by iron atoms produces mainly 0.85 MeV and 1.24 MeV γ rays. However, neutron capture by Fe^{56} produces metastable Fe^{57} with γ-ray energies up to 10 MeV. The total number of neutrons and photons generated per reacting neutron is about three. The coupling angle between the chamber and the detector is about tenfold greater for the scattered neutrons and γ rays than for the neutrons generated at the implosion focus. Consequently, the scintillator is far more efficient in detecting the indirect scattered neutrons and γ

rays than the direct neutrons from the implosion focus. Owing to the large attenuation of the inelastically scattered neutrons, the phenomenon is spread out and delayed as recorded in Fig. 2(b).

IV. DISCUSSION AND CONCLUSIONS

A consideration of the plasma parameters shows that the peak temperatures may be obtained at a radius of about 10 μm with an ion density of about 5×10^{22} ions/cm^3. The implosion time is then about 10^{-10} sec. Although radiation and conduction heat losses are significant, they would allow temperatures to be reached up to a few keV.

Discussions of different work, with greater complexity, to produce neutrons in deuterium by explosive means can be found in Ref. 5, as well as some considerations of the possibilities of scaling the present apparatus to obtain thermonuclear fusion. Here, we have shown that neutrons and γ rays can be obtained from nuclear reactions by very direct means from an explosive-driven hemispherical-implosion focus in D_2-O_2 mixtures. There is little doubt that temperatures in the keV range were reached thereby approaching thermonuclear fusion conditions. Much work remains to determine the details of the physical properties of such plasmas and the resulting nuclear collision processes.

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